*Binary Paths to Type Ia Supernovae Explosions*
*Proceedings IAU Symposium No. 281, 2011*
*R. Di Stefano & M. Orio eds.*

DOI: 00.0000/X000000000000000X



# Type Ia Supernovae and Supersoft X-ray Sources

**L.R. Yungelson**

Institute of Astronomy, RAS,
48 Pyatnitskaja Str., 119017 Moscow, Russia
email: lev.yungelson@gmail.com

**Abstract.** The rates of SN Ia for double-degenerate and single-degenerate scenario are computed for the models of spiral and elliptical galaxies. The number of nuclearly burning white dwarfs (NBWD) is traced. The data favours double-degenerate scenario and suggests lower number of NBWD per unit mass in ellipticals and their lower average mass as one of the reasons for the difference in the number of supersoft X-ray sources observed in the galaxies of different types.

**Keywords.** stars:binaries, stars:supernovae, X-rays: binaries

## 1. Introduction

While there exists an agreement that SN Ia result from thermonuclear explosions of white dwarfs (WD) which accumulated Chandrasekhar mass $M_{Ch} \approx 1.38 M_\odot$ (Hoyle & Fowler 1960), the process of accumulation of $M_{Ch}$ remains an enigma. It was suggested that WDs may accumulate $M_{Ch}$ via accretion in semidetached binaries (single-degenerate scenario, SD, Schatzman 1963), merger of binary WDs with $M_1 + M_2 \gtrsim M_{Ch}$ (double-degenerate scenario, DD, Webbink 1979), accretion of wind matter in symbiotic stars (Truran & Cameron 1971). It is also hypothesized that accretion of He onto sub-Chandrasekhar CO WD may lead to SN Ia via double-detonation (Livne 1990).

However, at the moment, only SD- and DD-scenario may be discussed as viable ones. Accretion in wide symbiotic systems is most probably not efficient enough for accumulation of $M_{Ch}$. Double-detonation scenario, though claimed to provide "correct" delay-time distribution of SN Ia (DTD) and enable a significant fraction of the total SN Ia rate (Ruiter et al. 2011), very strongly depends on the assumed efficiency of He-accumulation (Piersanti et al., these proceedings). Also, models do not fit observables, due to the presence of He-burning products in the outer layers of ejecta.

The count of supersoft X-ray sources (SSS) in external galaxies may provide certain clues to the problem of progenitors of SN Ia (Di Stefano 2010, Gilfanov & Bogdán 2010). SSS, which are deemed to be nuclearly burning white dwarfs (NBWD, van den Heuvel et al. 1992), may be direct precursors of SN Ia in the SD-scenario. In the DD-scenario, a binary may be a SSS when the first-formed WD accretes matter from the stellar wind of the precursor of the second WD. The number of observed SSS provides the lower limit of the number of NBWD, since the latter do not necessarily radiate in X-ray.

Below, we consider the relations between the rates of formation of NBWD, SN Ia, SSS in the model of stellar system with a constant for 10 Gyr star formation rate $\dot{M}_\star = 8\ \mathrm{M}_\odot\ \mathrm{yr}^{-1}$ and for a model in which the same mass of stars is formed in a 1 Gyr long star-formation burst, i.e. for toy-models of a spiral and an elliptical galaxy. We test also the influence of CE parameters and mass accumulation efficiency upon DTD. Our assumptions are described in Yungelson (2010). Note, we do not consider effects like "stripping" or "companion reinforced attrition process".

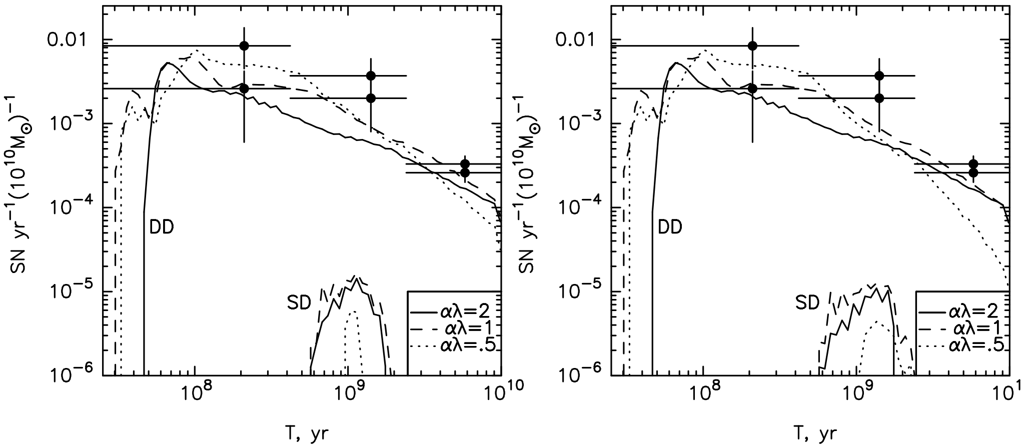


**Figure 1.** Model DTD for DD- and SD-scenarios compared to the observational data (Maoz et al. 2011). Two sets of the latter correspond to different models of the dust. Left panel — H- and He-accumulation efficiency after Prialnik & Kovetz (1995) and Iben & Tutukov (1996), right panel — efficiency after Hachisu et al. (1999) and Kato & Hachisu (2004).

## 2. Results

In Fig. 1 we compare DTD for DD- and SD-scenarios obtained for different values of the common envelope (CE) efficiency and donor envelope binding energy parameter product $\alpha_{ce} \times \lambda$ in Webbink's (1984) equation for CE. Total dominance of DD mergers is clear, irrespective of assumptions on $\alpha_{ce} \times \lambda$ and efficiency of matter accumulation. The main reason for this is a narrow range of combinations of masses of components in semidetached systems which allows steady accumulation of the matter. Bearing in mind all uncertainties involved in population synthesis and in derivation of DTD from observations, the slope of the model DD DTD ($t^{-0.8}$) compares well with the slope of DTD curve ($t^{-1.2\pm0.3}$ at $t \gtrsim 400$ Myr) derived by Maoz et al. (2011) for SN Ia at $0 < z < 1.45$.

Figure 2 shows results of computations for two model stellar systems. Formation rate of close binary WD reflects SFR, hence, SN Ia in the DD-scenario start at the age of several tens of Myr when the most massive pairs of WD begin to form. In the "spiral" galaxy binary WD form continuously and DD-SN Ia rate permanently increases, since merge both "old" initially relatively wide pairs and "young" relatively close ones. In the "elliptical" galaxy the reservoir of binary WD created in the star-formation burst gradually "melts" and soon after cessation of star formation DD-SN Ia rate starts to decline.

In semidetached systems SN Ia are delayed by $\sim 10^9$ yr respective to star formation. After a star-formation burst, semidetached systems in which a CO WD is able to accumulate $M_{Ch}$ form and exist only over a limited time span of several Gyr (Canal et al. 1996 and numerous later papers). In our model, SN Ia occur in binaries with $M_{wd,0} \gtrsim 0.85\,M_\odot$ and $M_{sg,0} \gtrsim 1.4\,M_\odot$ at the beginning of Roche-lobe overflow. Figure 2 shows that formation rate of semidetached systems with NBWD able to accumulate $M_{Ch}$ is only a minor fraction of the total formation rate of systems with NBWD even in the relatively early stages of evolution. Semidetached systems with NBWD form continuously, but *in the case of burst-like star formation currently observed SSS are not precursors of* SN Ia. The epoch of SN Ia in semidetached systems is short: in the model "spiral" galaxy at $t = 10$ Gyr SN Ia occur in stars formed approximately 600 Myr to 2.5 Gyr ago.

The phenomenon of symbiotic stars is associated predominantly with wide binaries, in which WD form neither through RLOF nor CE. As the donor begins to ascend the

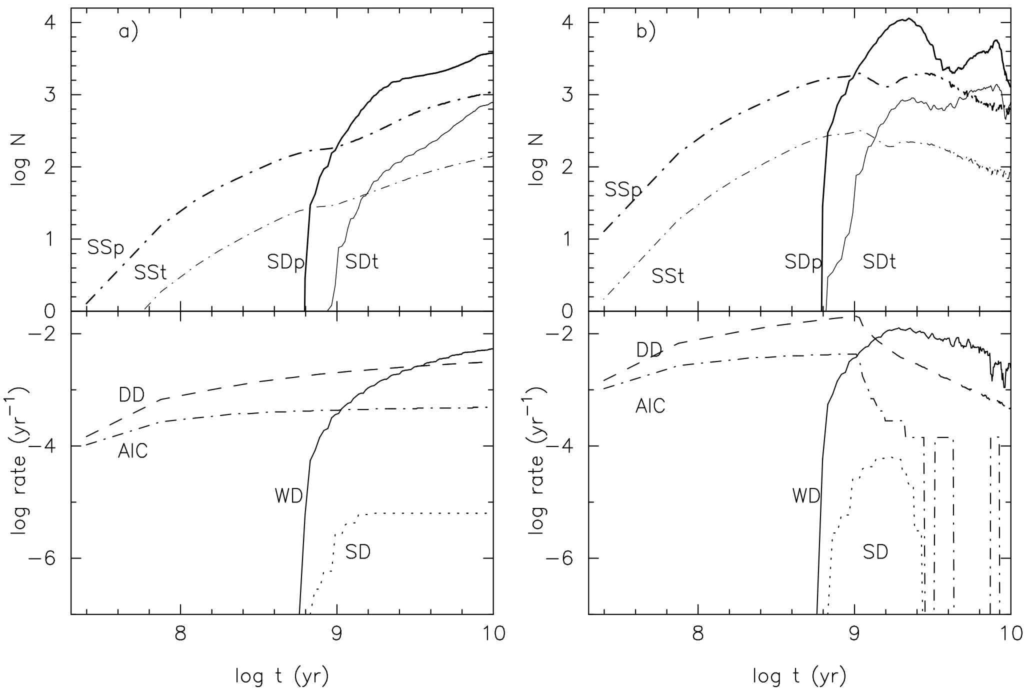


**Figure 2.** Panel (a), lower part — evolution of the rates of SN Ia in DD-scenario (dashed line) and in SD-scenario (dotted line), formation of NBWD (solid line), AICs in symbiotic stars in the model of a "spiral" galaxy. Upper part — evolution of the numbers of permanent (SSp) and transient (SSt) SSS in symbiotic stars and permanent (SDp) and transient (SDt) sources in semidetached systems. Panel (b) shows evolution of the same rates and numbers in the model of an "elliptical" galaxy.

giant branch, its stellar wind is weak and in a binary with $P_{\rm orb} \sim (100 - 1000)$ day accretion is extremely inefficient. Newborn NBWD first becomes an unstable burner and, typically, it may become a stationary burner only shortly before the loss of the envelope by companion (Yungelson et al. 1995). The amount of matter which may be retained by WD is as a rule $\lesssim 0.1\,M_\odot$ (Lü et al. 2006). An implication of this is that CO WD with $M_0 \lesssim 1.1 - 1.2\,M_\odot$ hardly reach $M_{Ch}$, while more massive ONeMg WD experience accretion-induced collapses (AIC, Nomoto & Kondo 1991). AIC's may explain the weakest peculiar SN Ia (Metzger et al. 2009). Evolution of the rate of AIC's in the models is also shown in Fig. 2.

In Fig. 3 we show the distribution of NBWD over masses in two models. Distributions sum up both transient and permanent burners. At any time the latter dominate due to longer lifetimes. In the systems with subgiants the fraction of outbursting systems is initially low, since first start to overfill their Roche lobes relatively massive stars with high $\dot{M}$. Later, the fraction of systems in which the rate of accretion is lower than the limit for stable H-burning increases, since the systems with massive donors finish their evolution fast. At $t$=10 Gyr, the number of NBWD in a "spiral" galaxy exceeds their number in an "elliptical" galaxy of the same mass and masses of WD are also higher (Fig. 3). Relatively well studied nearby spiral galaxies contain $\sim 100$ SSS each, while elliptical galaxies host only $\sim 10$ SSS per galaxy (Di Stefano 2010). Taking into account that *Chandra* is able to observe in these spiral galaxies only SSS with $M_{wd} \gtrsim (1.0 - 1.2)\,M_\odot$ and objects with $M_{wd} \gtrsim 0.8\,M_\odot$ in elliptical galaxies (Di Stefano 2010), the number of NBWD in the

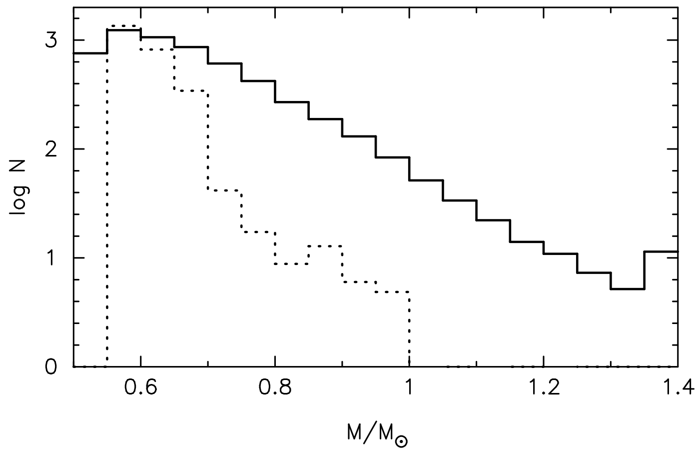


**Figure 3.** Mass spectrum of NBWD in the model systems with continuous star formation (solid line) and with initial starburst (dotted line). The histograms show total contribution of semidetached and symbiotic systems.

models at least qualitatively agrees with the one expected from observations. This brings to conclusion that the model in which the rate of SN Ia is defined by DD-mechanism and which is reasonably consistent with observationally inferred DTD, is also able to explain, at least partially, the difference in the numbers of SSS in spiral and elliptical galaxies.

The author acknowledges support from IAU, RFBR (grant No. 10-02-00231), and the Program of the Russian Academy of Sciences "Origin and evolution of stars and galaxies".

## References

Canal, R., Ruiz-Lapuente, P., & Burkert, A. 1996, *ApJ Lett.*, 456, L101
Di Stefano, R. 2010, *ApJ*, 712, 728
Gilfanov, M., & Bogdán, Á. 2010, *Nature*, 463, 924
Hachisu, I., Kato, M., & Nomoto, K. 1999, *ApJ*, 522, 487
Hoyle, F., & Fowler, W. A. 1960, *ApJ*, 132, 565
Iben, I., Jr., & Tutukov, A. V. 1996, *ApJS*, 105, 145
Kato, M., & Hachisu, I. 2004, *ApJ Lett.*, 613, L129
Livne, E. 1990, *ApJ Lett.*, 354, L53
Lü, G., Yungelson, L., & Han, Z. 2006, *MNRAS*, 372, 1389
Maoz, D., Mannucci, F., Li, W., Filippenko, A. V., Della Valle, M., & Panagia, N. 2011, *MNRAS*, 412, 1508
Metzger, B. D., Piro, A. L., & Quataert, E. 2009, *MNRAS*, 396, 1659
Nomoto, K., & Kondo, Y. 1991, *ApJ Lett.*, 367, L19
Prialnik, D., & Kovetz, A. 1995, *ApJ*, 445, 789
Ruiter, A. J., Belczynski, K., Sim, S. A., Hillebrandt, W., Fryer, C. L., Fink, M., & Kromer, M. 2011, *MNRAS*, 1282
Schatzman, E. 1963, Star Evolution, 389
Truran, J. W., & Cameron, A. G. W. 1971, *Ap&SS*, 14, 179
van den Heuvel, E. P. J., Bhattacharya, D., Nomoto, K., & Rappaport, S. A. 1992, *Astron. Astrophys.*, 262, 97
Webbink, R. F. 1979, IAU Colloq. 53: White Dwarfs and Variable Degenerate Stars, 426
Webbink, R. F. 1984, *ApJ*, 277, 355
Yungelson, L., Livio, M., Tutukov, A., & Kenyon, S. J. 1995, *ApJ*, 447, 656
Yungelson, L. R. 2010, *Astron. Lett.*, 36, 780